Porous Asphalt Pavements – Not Just for Parking Lots Anymore!

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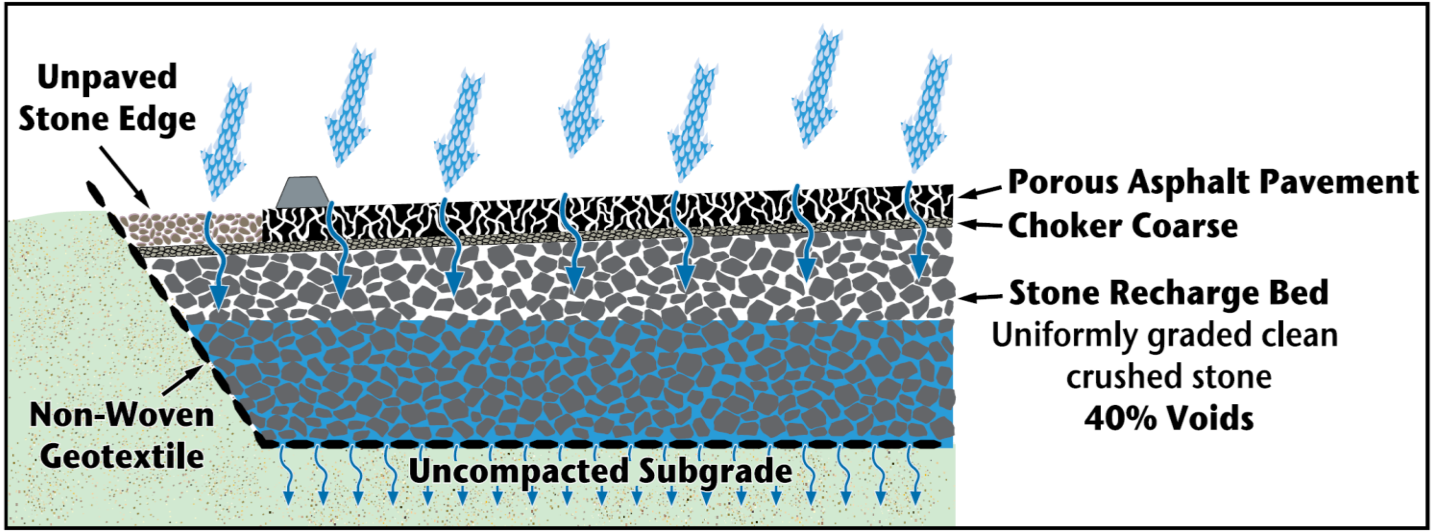
Background

http://www.pavementinteractive.org

Porous Pavements



National Asphalt Pavement Association, IS-131

Hydrologic Characteristics:

- Subgrade infiltration rate: 0.1 to 10 inches/hour
- Time to drain, stone recharge bed: 12 to 72 hours

Stone Recharge Bed typical thickness: 12 to 36 inches

Scope

✓ **Structural Design of Porous Asphalt Pavements**

Ensuring the Pavement Structure Can Carry the Design Traffic Loads

✗ Site selection

✗ Hydrologic design

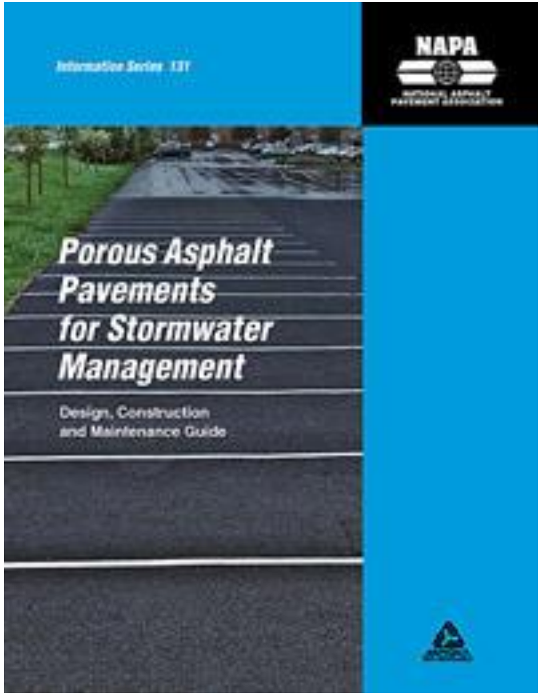
✗ Mixture design

✗ Construction

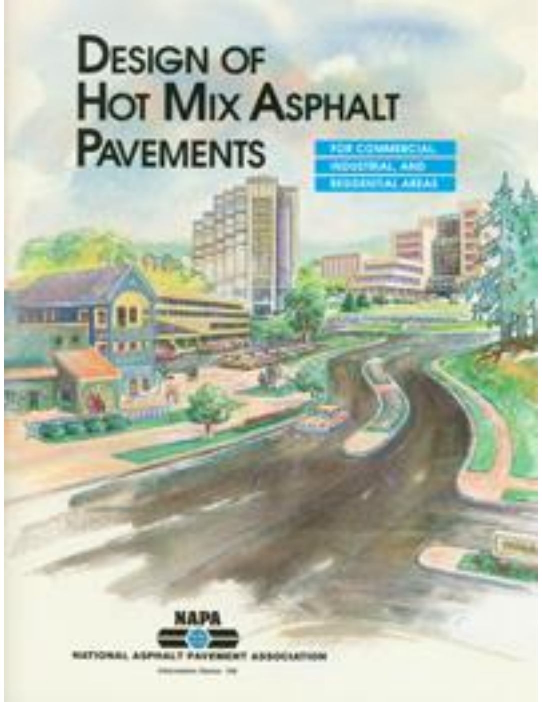
✗ Maintenance

http://theasphaltpro.com/when-it-rains-it-porous/

Additional Information Sources

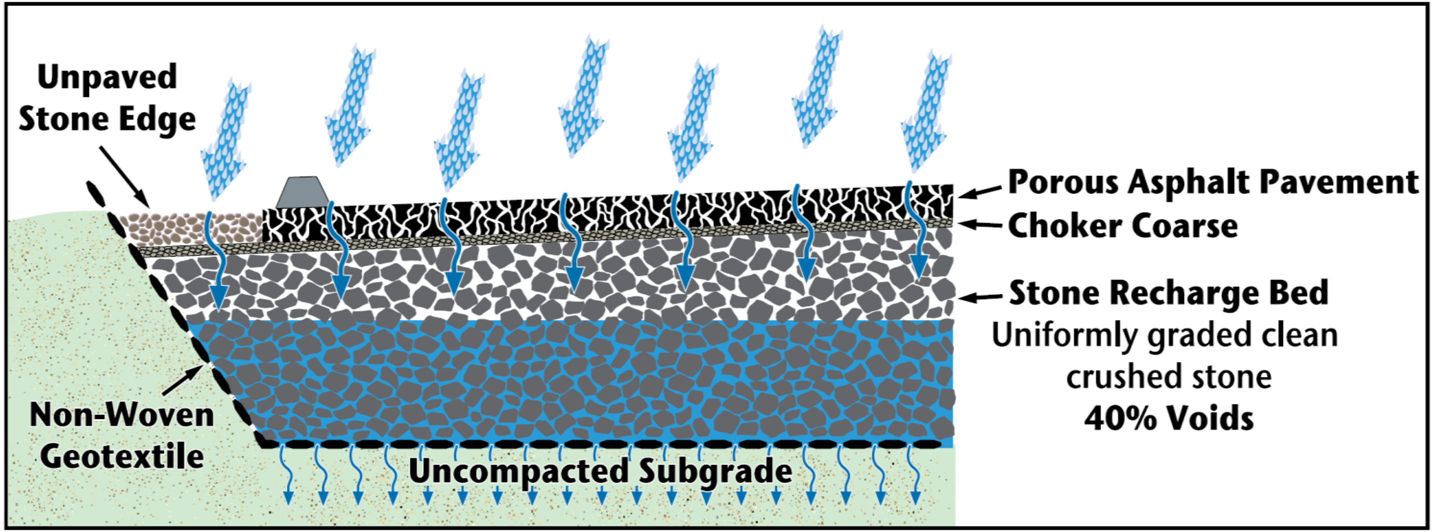


NAPA Information Series 131



NAPA Information Series 109

Porous Pavements



National Asphalt Pavement Association, IS-131

Porous vs. Conventional Pavements (1)

Pavement Layer	Purpose	Material(s)	Purpose	Material(s)
	Porous Asphalt		*Conventional Flexible*	
Asphalt Surface	Provide stable wearing surface; allows infiltration of water to stone recharge bed	Open-graded asphalt concrete; minimal compaction; interconnected voids; high air voids (typically 15 to 20% or more); permeable	Provide stable wearing surface; maintain ride quality; prevent water infiltration into the underlying layers; reduce traffic-induced stress/strain to underlying layers	Dense-graded asphalt concrete; low air voids (typically <8%); relatively impermeable; may have 1, 2, or 3 lifts of varying aggregate size.

Porous vs. Conventional Pavements (2)

Pavement Layer	Purpose	Material(s)	Purpose	Material(s)
	Porous Asphalt		*Conventional Flexible*	
Base Layer(s)	"Choker Course" - stable surface for subsequent paving	Clean, single-sized crushed stone	Provide structural capacity to pavement system; reduce traffic-induced stress/strain on subgrade	Dense-graded crushed stone
	"Recharge Bed" - stormwater storage	Clean, single-sized large crushed stone with high void ratio (typically ~40%)		
	"Separation Layer" - prevents migration of fine subgrade material to recharge bed	Geotextile fabric		

Porous vs. Conventional Pavements (3)

Pavement Layer	Purpose	Material(s)	Purpose	Material(s)
	Porous Asphalt		*Conventional Flexible*	
Subgrade	Provide infiltration of stormwater	Natural or select material (ideally, low fines content); typically uncompacted or only lightly-compacted to promote infiltration	Provide stable platform for pavement structure	Natural or select material; typically compacted to high percentage of maximum density

Structural Design

http://www.pavementinteractive.org

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Structural Design Methodology

Empirical AASHTO Flexible Pavement Design Equation (1993):

$$\log_{10} w_{18} = z_R * s_o + 9.36*\log_{10}(SN+1) - 0.2 + \frac{\log_{10}\left[\frac{\Delta PSI}{4.2-1.5}\right]}{0.40+\frac{1094}{(SN+1)^{5.19}}} + 2.32*\log_{10} M_R - 8.07$$

***SN* = required Structural Number (structural capacity) of the pavement**

w_{18} = number of 18-kip equivalent single axle loads (ESALs) expected over design life
z_R = standard normal deviate (level of design reliability)
s_o = standard deviation
⊗*PSI* = allowable change in the Present Serviceability Index (PSI) over design life
M_R = subgrade resilient modulus (psi)

Structural Design Methodology

Empirical AASHTO Flexible Pavement Design Equation (1993):

$$\log_{10} w_{18} = z_R * s_o + 9.36 * \log_{10}(SN+1) - 0.2 + \frac{\log_{10}\left[\dfrac{\Delta PSI}{4.2-1.5}\right]}{0.40 + \dfrac{1094}{(SN+1)^{5.19}}} + 2.32 * \log_{10} M_R - 8.07$$

SN* = design Structural Number of the pavement = *DESIGN OUTPUT

$SN = D_1 a_1 + D_2 a_2 m_2$

D_1 = thickness of asphalt layer
a_1 = structural layer coefficient for asphalt
D_2 = thickness of granular base (stone recharge bed)
a_2 = structural layer coefficient for granular base
m_2 = moisture/drainage coefficient for granular base

Design Traffic

W_{18}

(ESAL)

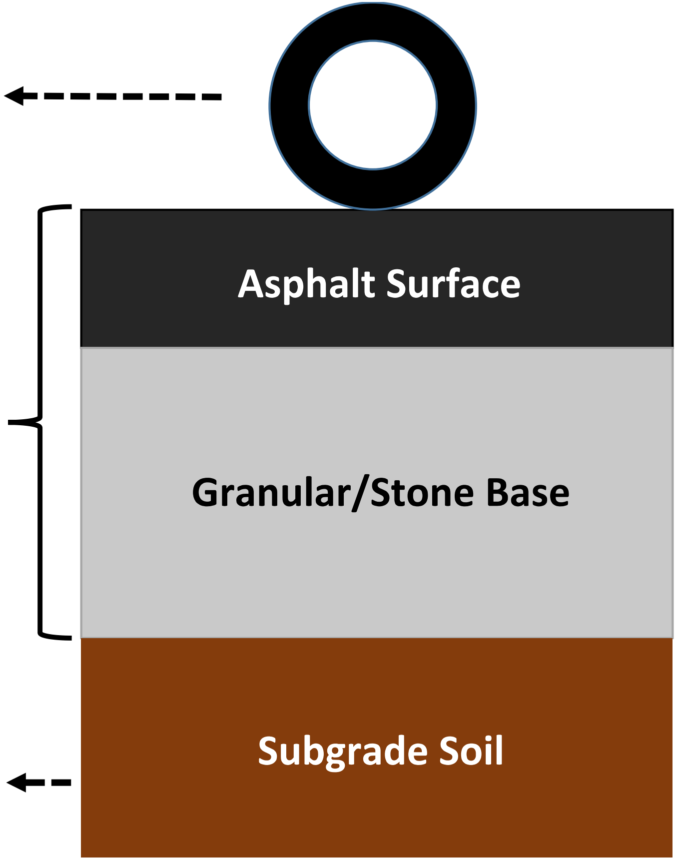
AASHTO Design Equation:

$\mathbf{SN_{design}}$ of Pavement Structure

Subgrade Resilient Modulus

M_R

(psi)



$\mathbf{SN_{design}} \leq \mathbf{SN_{pvmt}}$

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a_i = structural coefficient
d_i = thickness (in)
m_i = drainage coefficient

$$a_1 * d_1 = SN_1$$

$$+$$

$$a_1 * d_1 * m_2 = SN_2$$

$$SN_1 + SN_2 = SN_{pvmt}$$

Structural Design Inputs (1)

AASHTO Design Equation: Design Traffic w_{18} (ESALs)

Use existing agency procedure for estimating design traffic or the NAPA Traffic Classifications:

Type of facility and vehicle types	Maximum trucks per month (one lane)	Traffic class	Design period (years)	Design ESALs
Residential driveways, parking stalls, parking lots for autos and pickup trucks.	<1	Class I	5 10 15 20	3,000 3,000 5,000 7,000
Residential streets without regular truck traffic or city buses; traffic consisting of autos, home delivery trucks, trash pickup, occasional moving vans, etc.	60	Class II	5 10 15 20	7,000 14,000 20,000 27,000
Collector streets, shopping center delivery lanes; up to 10 single-unit or 3-axle semi-trailer trucks per day or equivalents; average gross weights should be less than the legal limit.	250	Class III	5 10 15 20	27,000 54,000 82,000 110,000
Heavy trucks; up to 75 fully loaded 5-axle semi-trailer trucks per day; equivalent trucks in this class may included loaded 3-axle and 4-axle dump trucks, gross weights over 40,000 lbs.	2200	Class IV	5 10 15 20	270,000 540,000 820,000 1,100,00

NAPA Information Series 109, Design of Hot-Mix Asphalt Pavements for Commercial, Industrial, and Residential Areas

Structural Design Inputs (2)

AASHTO Design Equation: Reliability, Standard Deviation, ΔPSI

Design Reliability

Reliability (%)	Std Normal Deviate, Z_R
50	0.000
75	-0.674
80	-0.842
90	-1.282
95	-1.645
99.99	-3.719

Standard Deviation

Typical values for the AASHTO flexible pavement equation:

0.42 – 0.49

ΔPSI

$\Delta PSI = p_0 - p_t$

p_0 Initial serviceability index; typical values: 4.2 – 4.5

p_t Terminal serviceability index; typical values: 2.0 – 2.5

Typical Values for ΔPSI:
2.0 – 2.5

Structural Design Inputs (3)

AASHTO Design Equation: Subgrade Resilient Modulus M_R

- Resilient modulus for existing subgrade soil
  - NAPA Subgrade Classification Guide (next slide)
- Typical modulus values in NAPA table be reduced by 25 to 50%
  - Subgrades typically uncompacted/lightly compacted
  - Subgrades typically at higher moisture contents
- Composite subgrade modulus for structural pavement design
  - Accounts better for thick stone recharge bed
  - Procedure described later

Subgrade Classification Guide with Typical Resilient Modulus (M_R) Values

NAPA Information Series 109, Design of Hot-Mix Asphalt Pavements for Commercial, Industrial, and Residential Areas (2002)

Soil Type	Unified Soil Class	Percent Finer Than 0.02mm	Permeability	Frost Potential[1]	Typical CBR[2]	Design Class	Typical Flexible Pavement M_r (psi)[2]	Recommended Porous Pavement M_r (psi)[2]
Sands, sand-gravel mix Little or no fines <0.02mm	SW,SP	0 – 3	Excellent	NFS	17	Very Good	20,000	20,000
Sands, sand-gravel mix Some fines <0.02mm	SW,SP	1.5 – 3	Good	PFS	17	Very Good	20,000	20,000
Sandy soils Medium fines <0.02mm	SW,SP,SM	3 – 6	Fair	Low	8	Good	12,000	9,000
Silty gravel soils High fines <0.02mm	GM GW-GM,GP-GM	6 – 10 10 - 20	Fair to Low	Medium	8	Good	12,000	9,000
Silty sand soils High fines <0.02mm	SM SW-SM,SP-SM	6-15	Fair to Low	Medium	8	Good	12,000	9,000
Clayey sand soils High fines <0.02mm	SM,SC	Over 20	Low to Very Low	Medium to High	5	Medium	7,500	3,750
Clays, PI>12	CL,CH		Very Low	High[3]	3	Poor	4,500	2,250
All silt soils	ML,MH		Very Low	High to V.High[3]	3	Poor	4,500	2,250
Clays, PI<12	CL,CL-CM		Very Low	High to V.High[3]	3	Poor	4,500	2,250

[1]NFS = not frost susceptible; PFS = possible frost susceptible

[2]CBR = California Bearing Ratio and Mr = Resilient Modulus values are minimum values expected for each subgrade class

[3]Replace in severe frost areas

(Excerpts)

Structural Design Inputs (4)

AASHTO Design Equation: Layer coefficients a_i

Porous Asphalt Surface: **a_1 = 0.40**

- Typically placed at low densities
- Typically features open gradations

Asphalt-Treated Permeable Base (ATPB): **a_2 = 0.30 to 0.33**
(if present)

Coarse Aggregate Base (Stone Recharge Bed): **a_2 = 0.07 to 0.10**

- Typically placed at high void contents (lower stiffness, e.g. 15 ksi)
- AASHTO stiffness relationship for granular base:

$$a_2 = 0.247(\log_{10} E_{base}) - 0.977$$

Structural Design Inputs (5)

AASHTO Design Equation: Drainage coefficient m_2

Aggregate Base
(Stone Recharge Bed)

Applies to unbound materials only

(Coarse Aggregate Base [Stone Recharge Bed])

- AASHTO relationship based on "quality" of drainage (time to drain) and percent time near saturation

For Porous Asphalt pavements:

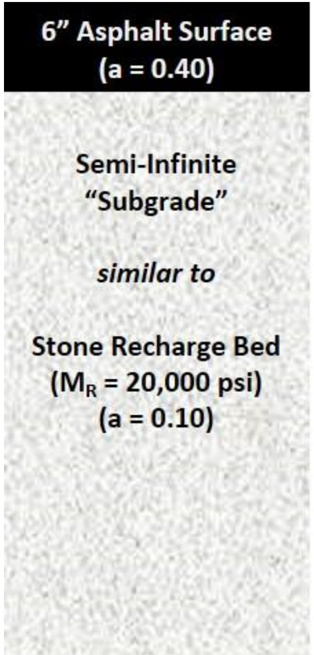
- Assumed drainage quality is GOOD (water removed in ~1 day)
- Assumed time near saturation is 5-25%

Quality of Drainage	Water Removed Within	Percent of Time Pavement is Exposed to Moisture Levels Approaching Saturation			
		<1%	1-5%	5-25%	>25%
Excellent	2 hours	1.40-1.35	1.35-1.30	1.30-1.20	1.20
Good	1 day	1.35-1.25	1.25-1.15	1.15-1.00	1.00
Fair	1 week	1.25-1.15	1.15-1.05	1.00-0.80	0.80
Poor	1 month	1.05-0.80	1.05-0.80	0.80-0.60	0.60
Very Poor	> 1 month	0.95-0.75	0.95-0.75	0.75-0.40	0.40

For porous pavement design, use $m_2 = 1.0$ for all situations

Base Effective Thickness

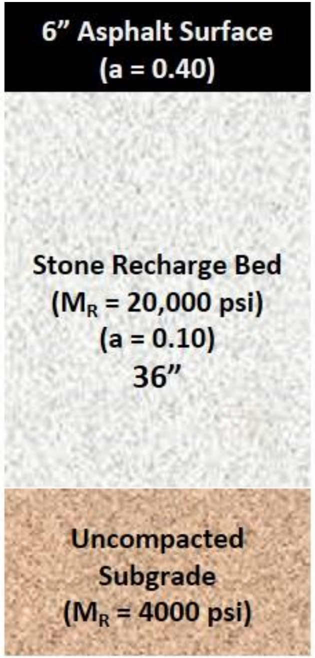
http://www.pavementinteractive.org



SN_1= 2.4

From the AASHTO Design Equation:
Reliability = 75% (z_R = -0.674)
Std. Deviation (So) = 0.45
Change in PSI (ΔPSI) = 2.5 (p_0=4.5; p_t=2.0)
Subgrade Modulus (M_R) = 20,000 psi
Structural Number (SN) = 2.40

→ Allowable Traffic **2.3M ESALs**



SN_1= 2.4

SN_2= 3.6

From the AASHTO Design Equation:
Reliability = 75% (z_R = -0.674)
Std. Deviation (So) = 0.45
Change in PSI (ΔPSI) = 2.5 (p_0=4.5; p_t=2.0)
Subgrade Modulus (M_R) = 4000 psi
Structural Number (SN) = 6.0

→ Allowable Traffic **41.5M ESALs!!**

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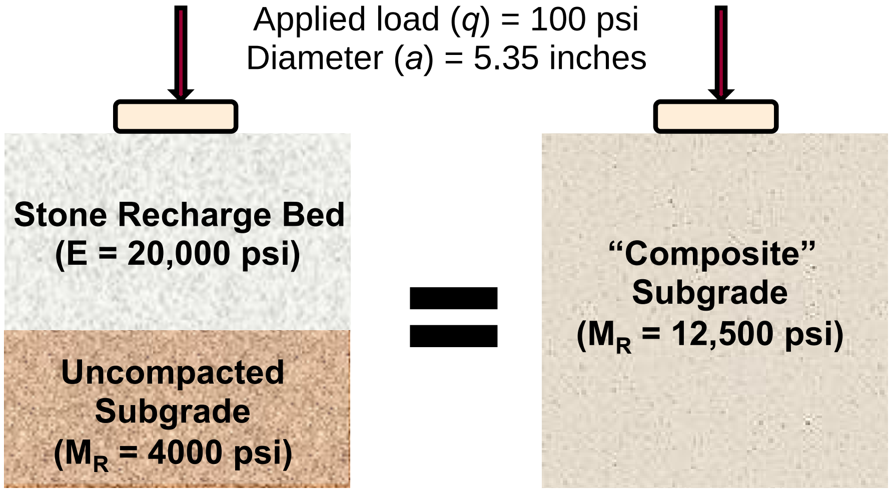
A Problem…

How can a weaker pavement section carry **20x** more traffic??

Composite Subgrade Concept

These two cross-sections are ***structurally* equivalent** based on equal surface deflections from an applied load.



Burmister's Equation
For 2-layer systems:

$$w_o = \frac{1.5qa}{E_2} F_2$$

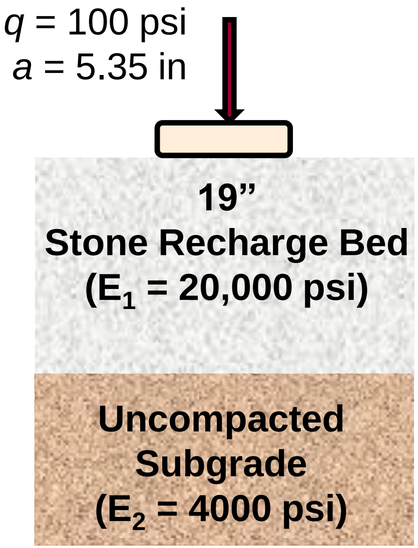
Burmister's Equation
For 1-layer systems:

$$w_o = \frac{1.5qa}{E}$$

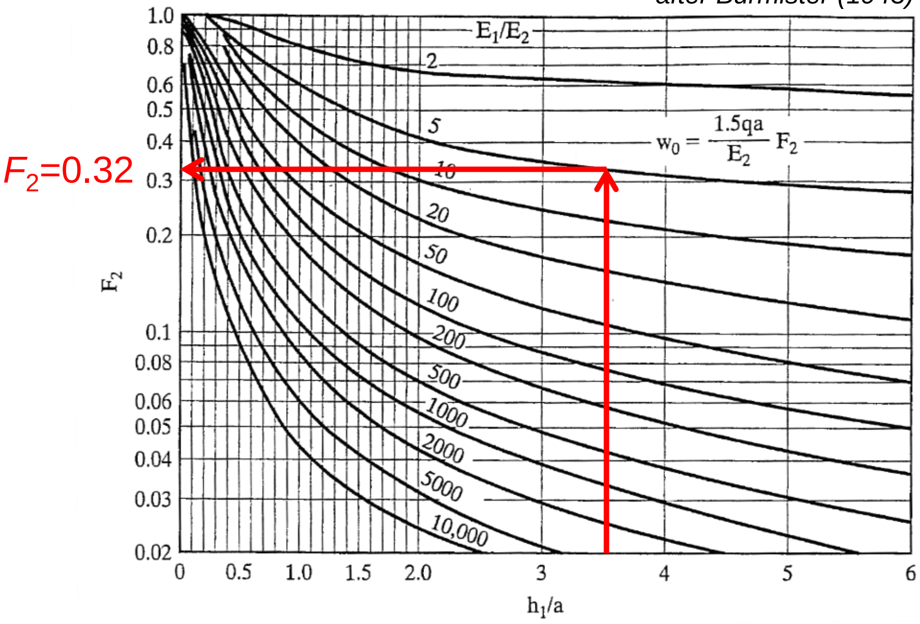
The analysis is based on elastic layer theory; the two-layer (stone over subgrade) system is converted to a one-layer ('composite' subgrade) system.

where:
w_0 = surface deflection (in)
q = applied load (psi)
a = load diameter (in)
E = single-layer modulus
E_2 = 'layer 2' modulus in 2-layer system (uncompacted subgrade)
F_2 = Burmister's 2-layer deflection factor

Deflection of Two-Layer System



after Burmister (1943)



E_1/E_2 = 20,000 psi / 4,000 psi = 5.0

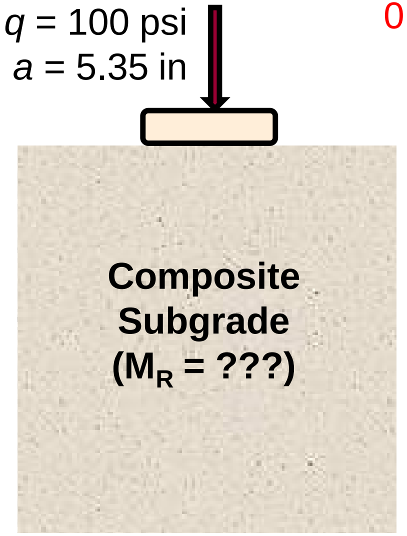
h_1/a = 19 in / 5.35 in = 3.55

Surface Deflection:

$$w_o = \frac{1.5qa}{E_2} F_2 = \frac{(1.5)(100\ \text{psi})(5.35\ \text{in})}{4000\ \text{psi}}(0.32) = 0.0642\ \text{in}$$

Composite Subgrade Stiffness of Equivalent One-Layer System

Target Equivalent Surface Deflection = 0.0642 in



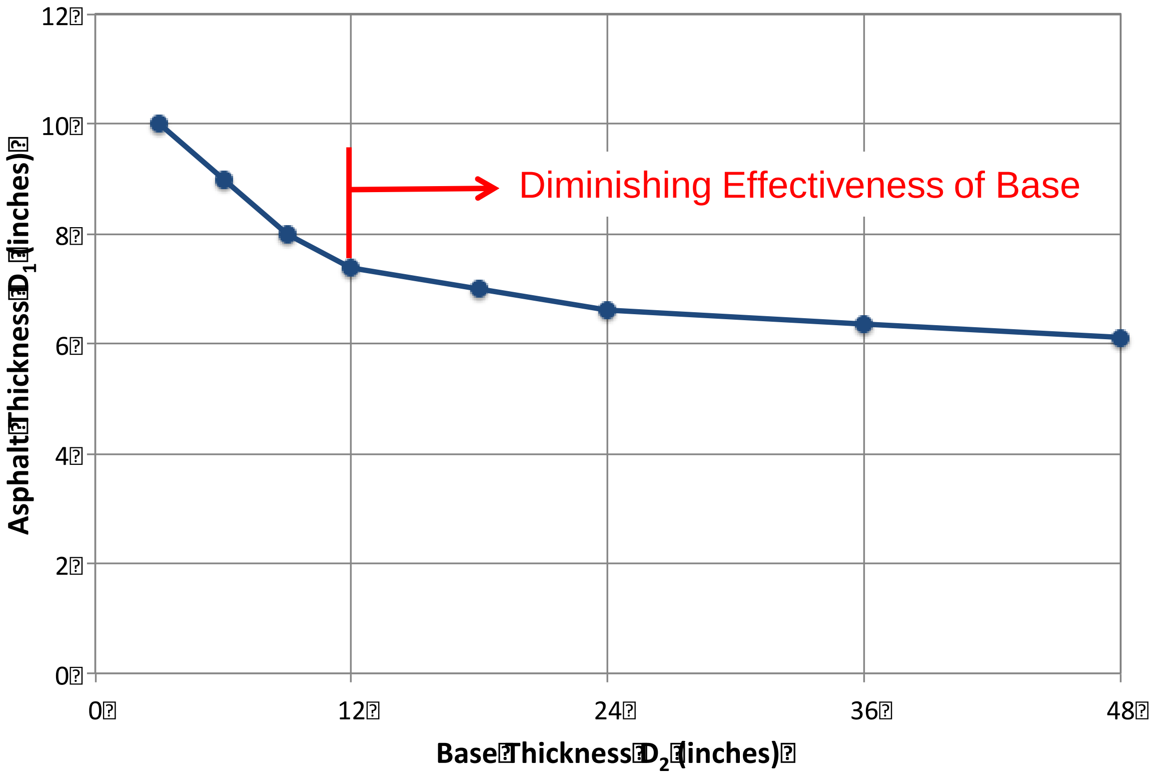
Surface Deflection for One-Layer System:

$$w_0 = \frac{1.5qa}{E}$$

Equivalent Composite Subgrade for One-Layer System:

$$E = \frac{1.5qa}{w_0} = \frac{1.5(100\text{ psi})(5.35\text{ in})}{0.0642\text{ in}} = 12{,}500\text{ psi}$$

Effective Thickness of Base Layer



Maximum base thickness at AASHO Road Test was 9 inches!

Design Example

http://www.pavementinteractive.org

Structural Design Methodology

Empirical AASHTO Flexible Pavement Design Equation (1993):

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SN = design Structural Number of the pavement = = $D_1a_1 + D_2a_2m_2$

w_{18} = number of 18-kip equivalent single axle loads (ESALs) expected over design life
z_R = standard normal deviate (level of design reliability)
s_o = standard deviation
ΔPSI = allowable change in the Present Serviceability Index (PSI) over design life
M_R = subgrade resilient modulus (psi)

Minimum Porous Asphalt Thickness (1)

***Given*:**

- Design traffic (project specific): **3M** ESALs (Heavy Trucks)
- Allowable deterioration (typical values and/or agency policy):
  - ⊗PSI = **2.5** (Initial PSI p_0 = 4.5; Terminal PSI p_t = 2.0)
- Reliability parameters (typical values and/or agency policy):
  - Reliability: **75%** (Z_R = -0.674)
  - Standard Deviation: **0.45**
- Stone recharge bed → **layer to be protected by asphalt layer**
  - Resilient Modulus: **20,000** psi

***Solve AASHTO Flexible Pavement Design Equation*:** $SN_1 = 2.55$

***Minimum asphalt thickness*:** $D_1 = SN_1/a_1 = 6.4$ in., **use D_1 = 6 inches**

Minimum Porous Asphalt Thickness (2)

W_{18} (ESALs)	Minimum Porous Asphalt Thickness (inches)
50,000	3.0
100,000	3.5
250,000	4.0
500,000	4.5
750,000	5.0
1,000,000	5.5
2,000,000	6.0
4,000,000	6.5

(a_1 = 0.1, E_{base} = 20,000 psi, 75% reliability, s_0 = 0.45, ΔPSI = 2.5)

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① *Design For Hydrologic Capacity*

(not covered here)

D_1 = 6”

D_2 = 19”

6” Asphalt Surface*
(a_1 = 0.40)

19”
Stone Recharge Bed
(M_R = 20,000 psi)
(a_2 = 0.10)

Uncompacted Subgrade
(M_R = 4000 psi)

*Maximum for hydrologic design

② *Determine Composite Subgrade Modulus*

(see previous slides)

M_R (existing) = 4000 psi

M_R (composite) = 12,500 psi

?” Asphalt Surface
(a_1 = 0.40)

“Composite” Subgrade
(M_R = 12,500 psi)

③ *Determine Structural Number Required for Future Traffic (SN_{design})*

(see previous slides)

W_{18} = 3.0M ESAL

R = 75% (Z_R = -0.674)
S_0 = 0.45
ΔPSI = 2.5

USE
M_R = 12,500 psi
(composite M_R)

SN_{design} = 2.94

④ *Determine Required Porous Asphalt Thickness (D_1)*

$SN_{design} = SN_1$
$SN_1 = D_1 * a_1$

SO…

$D_1 = SN_1 / a_1$
= **2.94** / 0.40

D_1 = 7.35”
or
D_1 = 7.5”
(for STRUCTURAL design)

Design Catalog Tables

For W_{18} = 3,000,000 ESAL

		Design Subgrade Resilient Modulus (psi)						
		2000	3000	4000	6000	8000	10000	12000
Base Thickness (inches)	6	11.5	10	9	8	7.5	7.5	7
	12	10	8.5	8	7.5	7	7	6.5
	18	8.5	8	7.5	7	7	7	6.5
	24	8	7.5	7.5	7	7	6.5	6.5
	30	7.5	7.5	7	7	6.5	6.5	6.5
	36	7.5	7	7	7	6.5	6.5	6.5
	42	7	7	7	6.5	6.5	6.5	6.5
	48	7	7	6.5	6.5	6.5	6.5	6.5

Required Porous Asphalt Thickness

(For thin bases, also use conventional AASHTO design and take most conservative case)

Design Assumption for Catalog Tables:

- a_1 = 0.40 (porous asphalt)
- a_2 = 0.10 (stone base)
- E_{base} = 20,000 psi (stone base)
- 75% reliability (Z_R = -0.674)
- s_0 = 0.45 (overall variability)
- ΔPSI = 2.5 (allowable serviceability decrease)
- a = 5.35 in (load radius)
- q = 100 psi (load pressure)

Values for composite subgrade modulus computation

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